Data Analysis: Plankton Distribution in Internal Waves in Massachusetts Bay

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LONG-TERM GOALS

Our long-term goals are describing and understanding the mechanisms responsible for plankton accumulation and transport in large amplitude internal waves.

OBJECTIVES

The general objective of our research is to observe the effect of tidally generated undular bores on near-surface plankton distribution. The particular objectives are (1) to determine the spatial scales of plankton distribution compared to the physical features before, during and after the internal tidal bores, and (2) to resolve whether plankton is concentrated by the physical characteristics of the bores. If there is a pattern in the plankton distribution associated to the bore, then another objective is (3) to determine whether plankton accumulation is dependent on plankton behavior, and to resolve whether taxa redistribute differentially in specific regions of the bore.

APPROACH

We are using an observational and theoretical approach (Pineda et al. 2002). Our observational program includes following internal bores as they propagate from Stellwagen bank to Scituate, in Massachusetts Bay. The bores are sampled with a shipboard Doppler current meter (velocity and backscatter), a 200 KHz backscatter transducer, and a towed video plankton recorder (VPR), which captures images, and records depth, conductivity, temperature, fluorescence, light attenuation and

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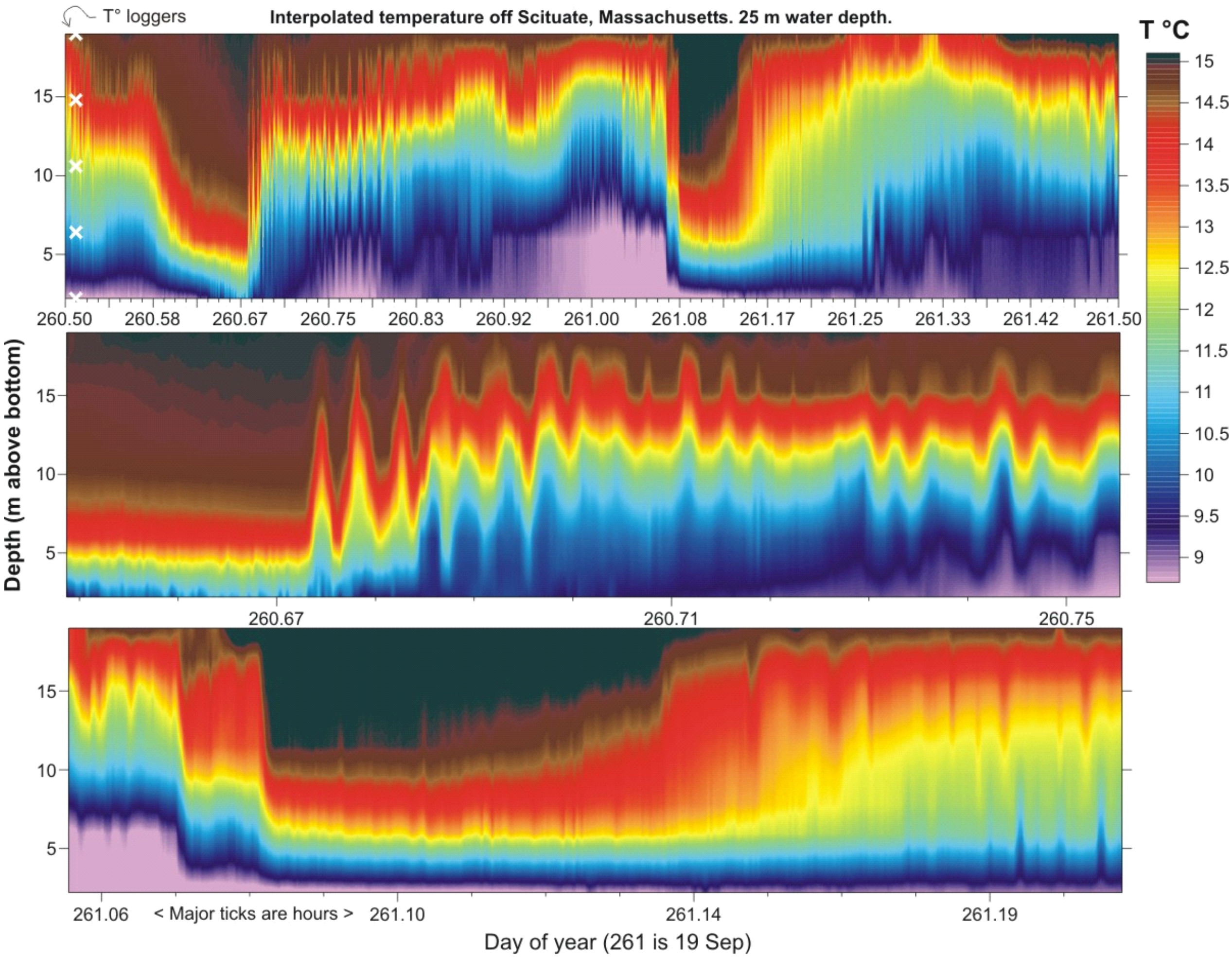

Figure 1. Time series of interpolated temperature at 25 water depth. The middle and bottom panels are amplifications of the bottom top panel. White crosses on the top panel indicate temperature logger position
[The top panel shows that the whole water column oscillated from warm to cold in about 12.h hours. The middle panel shows that when the temperature is cooling, higher-frequency (few minutes) internal waves of elevation lead the cooling. However, when the water column is warming periodic internal waves are missing.]

Photosynthetically Active Radiation. In addition bores are observed with moored instruments, including a moored video plankton observatory system ("AVPPO"), temperature moorings, and Doppler current meter profilers. Our observations on particle accumulation by the bores will be contrasted with an internal bore model (Scotti and Beardsley, ms. a & b). The bore model will also be used to guide our observational program. In general, Pineda and Gallager are responsible for the observational portion of the program, while Scotti is in charge of the theoretical aspect.

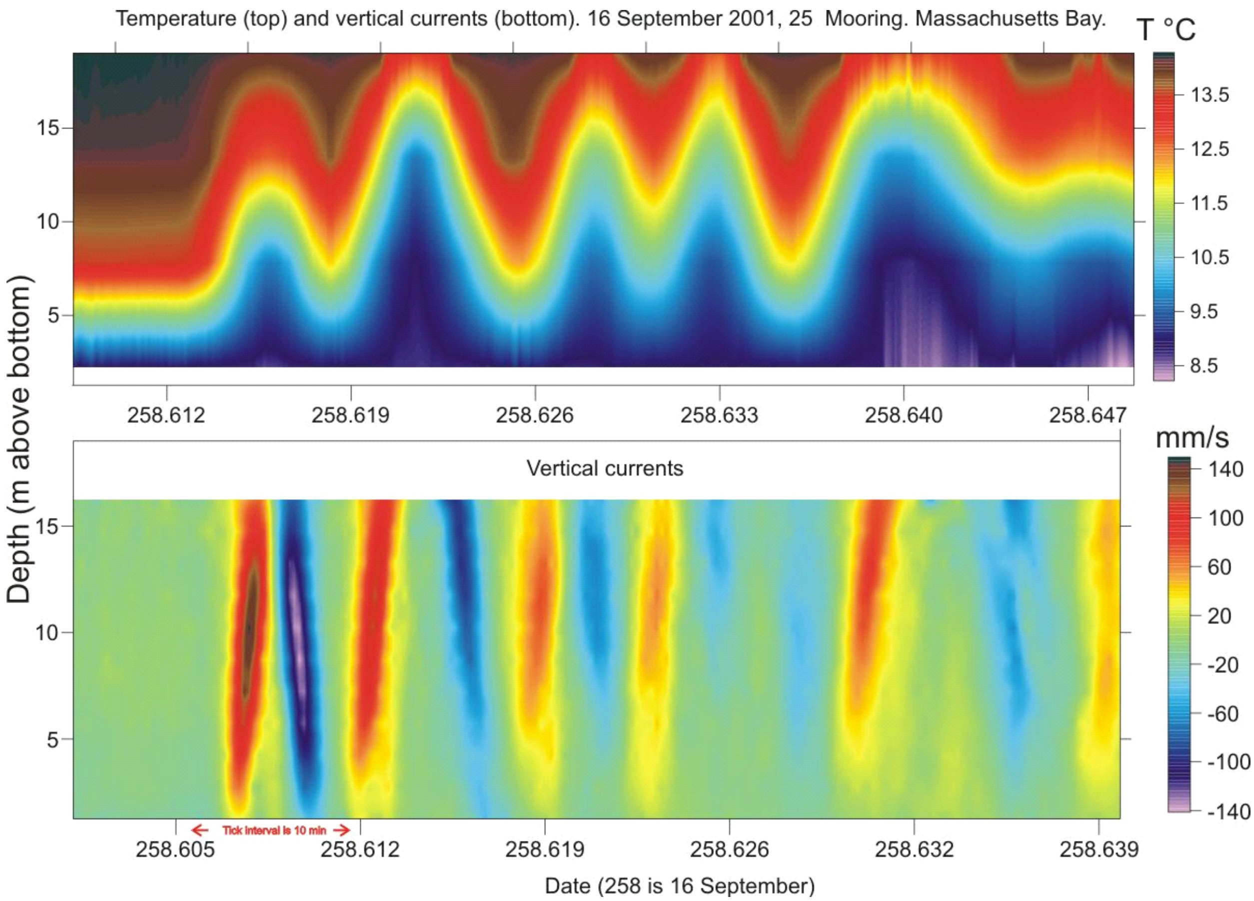

Figure 2. Time series (about 1 h) of interpolated temperature (top) and vertical currents (bottom) at 25 water depth. Temperature and 1200 kHz Doppler currentmeter moorings are separated a few 10's m. Sampling interval is 8 s for the temperature, 16 s and bin size is 0.75 m for the current meter. Panels are displaced to match temperature and circulation patterns. [The top panel shows a train of internal waves with periods of about 10 minutes and wave heights of up to 10 m. The bottom panel shows a pattern of upward and downward currents corresponding to the waves, with maximum upward and downward currents of 14 cm/s.

WORK COMPLETED

The fieldwork component consists of two cruises, one in 2001 and another in 2002. Both cruises used the R/V Connecticut. Work in the 2001 cruise was described in our previous report. In 2002 our cruise dates were from 30 September to 11 October. We deployed three temperature moorings, located at 25, 30 and 45 m water depth, and one Doppler current profiler at 45 m. The instruments acquired high frequency time series of temperature and water currents. We also obtained hourly profiles from seabed to surface of plankton, temperature, conductivity, fluorescence, light attenuation at 5 frequencies (AC-9), and up and down-welling irradiance with the AVPPO. We sampled several internal bore fronts as they propagated westward from Stellwagen bank, both during daytime and nighttime. Sampling was completed with the VPR (plankton, temperature, conductivity and depth) and with a shipboard 600 kHz Doppler current meter (backscatter, velocity), and a Biosonics 200 KHz system. We were unable to locate the internal wave packets at the beginning of the cruise, possibly because the high frequency motions dissipated before detection. By 3 October, however, we observed the first packet of many during the cruise. Because of gear malfunctioning, we returned to Woods Hole for one day, after which we sampled several more packets of internal bores. The data set is very rich, and the analysis of the physical data is well advanced.

To analyze the data, we have developed a new method to process raw ADCP data that, in addition to accounting for the spatial extension of the waves, provides an estimate of the direction and speed of propagation (Scotti et al., a ms.). The 2-Dimensional model of the internal tide in the bay is now completed, and was used to estimate the baroclinic energy flux (Scotti et al, b, ms.).

RESULTS

A preliminary analysis of the data recorded in the shallow water location (~25 m) shows an internal wave field characterized by the semidiurnal passage of a broad wave of depression (Fig. 1). High frequency waves of elevation are usually found on the trailing edge of the depression (Fig 1, starting

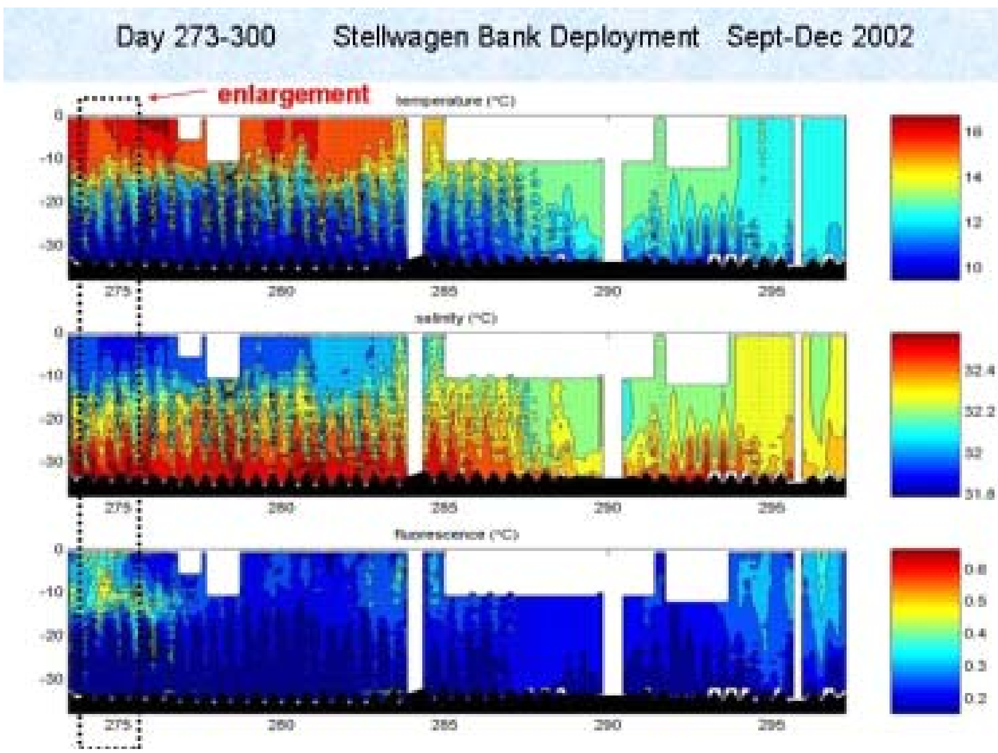

Figure 3. Time series of interpolated temperature, salinity and fluorescence obtained with the AVPPO (about 45 m water depth).
[The three panels show that the variability is dominated by oscillations with a period of about 12 h. After day 287, the layered patterns are much less conspicuous, indicating a reduction in the water column stratification.]

high frequency waves are found on the leading edge of the depression. From the timing and phase of these structures, and from the results of our numerical model, we infer that the broad waves of depression observed at the two sites and the undular bores observed in Stellwagen Basin (e.g. Haury et al. 1979, Chereskin 1983) are different expressions of the same disturbance that originates every tidal cycle over Stellwagen Bank and moves shoreward with an estimated phase speed ranging from 40 to over 70 cm/s. In deep water (~> 70 m), our shipboard observations show that the disturbance has the form of an undular bore of depression. As it moves into shallower waters, the bore looses its undular character, a feature that is predicted by our model and can be ascribed to the strongly nonlinear interaction with the shoaling bottom. During this process, part of the baroclinic energy originally contained in the undular bore is lost to dissipation, but a significant fraction (about 60 %) is transmitted onshore. There, the disturbance appears as a strongly nonlinear internal tide, which lowers and raises the thermocline over a period of a few hours. Often, the lowering of the thermocline is gradual. The restoring process, the cooling of the water column, is usually accompanied by the presence of high-frequency nonlinear waves of elevation, that can be occasionally very steep (see Figs. 1 and 2) and associated with large vertical velocities of up to 14 cm/s (Fig. 2). Using the method described above, we infer that the train of waves shown in figure 2 propagates to the WNW at 23 cm/s. Because the amplitude of the displacement is about 10 m (both integration of the vertical velocity and analysis of the temperature data support this estimate), the slope of the waves is O(1), which is far above the range of validity of current weakly nonlinear theories. To the best of our knowledge, this is the first time such extreme undular bores are observed in the ocean. The alternate presence of cold and warm bodies of water in the nearshore (Fig. 1) represents energetic cross-shore and vertical exchange of parcels of water at very short time scales, as described qualitatively by Pineda (1994). Thus, sharp semidiurnal variability occurs at both depth stations, but our preliminary observations suggest that the high-frequency waves of depression associated with the phase where the thermocline is deepening occurs mostly at the 45 m depth station. In contrast, waves of elevation predominate at 25 m and are associated with the leading edge of the shallowing of the thermocline.

Presence of such an energetic internal wave field, coupled with its relatively predictable nature, has important effects on the spatial and temporal distribution of zooplankton. A month long time series of data from the AVPPO shows the semidiurnal internal tide followed by disruption of stratification following passage of a storm (Figure 3). Figure 4 shows an expanded two day section of these data and select profiles of total zooplankton, dominated by krill and calanoid copepods.

The combination of towed VPR data and 200 KHz acoustic backscatter from the Biosonics unit revealed a strong association of plankton with temperature in the internal wave front, but on occasions the correspondence between plankton and acoustic backscatter was poor. This underscores the importance of measuring particle and plankton distributions independently of acoustics before acoustic backscatter can be interpreted correctly.

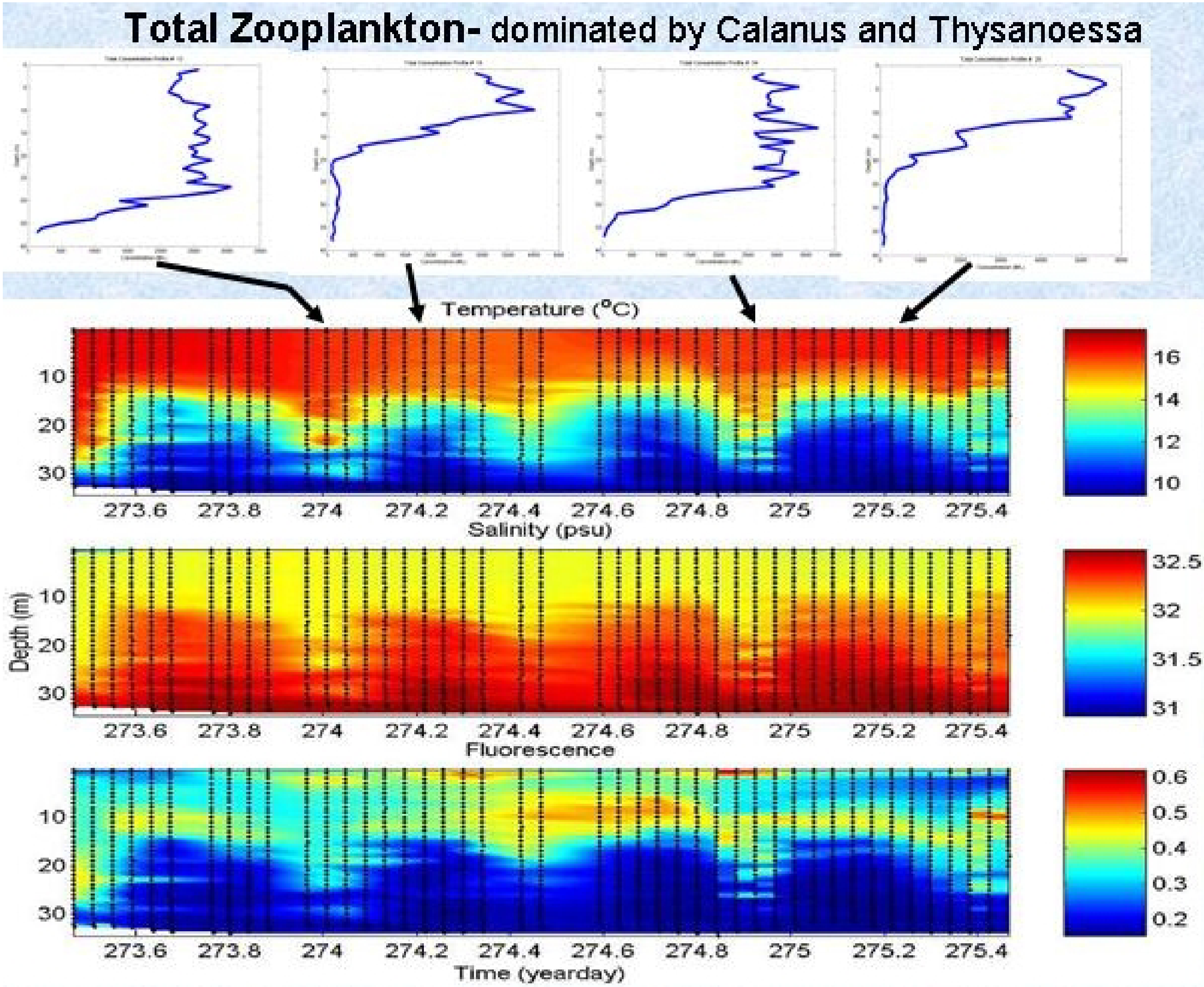

Figure 4. Zooplankton depth profiles, and time series of interpolated temperature, salinity and fluorescence obtained with the AVPPO (about 45 m water depth).
[The three bottom panels show that the variability is dominated by oscillations with a period of about 12 h. The three upper profiles show the vertical distribution of copepods and krill being compressed and expanded as the thermocline shallows and deepens.]

IMPACT/IMPLICATIONS

Our research will shed light on the formation and persistence of zooplankton patchiness by internal bores and waves, and whether zooplankton behavior influences this pattern. We will also contribute to the interpretation of acoustic backscatter information in relation to physical and biological properties of internal waves.

RELATED PROJECTS

Scotti is currently funded by the ONR to develop a comprehensive 3-dimensional model to study the interaction on nonlinear waves with topography. The data collected in shallow water will be used to validate the model.

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